

# On Star Formation Rate and Turbulent Dissipation in Galactic Models

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The models of star formation function and of dissipation of turbulent energy of interstellar medium are proposed. In star formation model the feedback of supernovae is taken into account. It is shown that hierarchical scenario of galaxy formation with proposed models of star formation and dissipation is able to explain the observable star formation pause in the Galaxy.

## Introduction

In models of evolution of galaxies where the direct gas-dynamical computation is used, it is difficult to reach the resolution in space less than 10 – 100 pc and resolution in time less than, say, 10<sup>5</sup> yr due to computational cost. We can use only the phenomenological approach to describe the interstellar medium (ISM) on scale 100 pc and below. This means that we have to use an averaged description of interstellar medium.

In the present paper we consider a star formation model dealing with turbulent energy of ISM and an averaged approach to take into account the structure of ISM in model of dissipation of turbulent energy.

The proposed models are able to explain the observable star formation pause in our Galaxy corresponding to star ages from 8 – 9 to 10 – 12 Gyr.

## Star formation model

The main factor which affects star formation is a gas density. However, it is clear that star formation can be suppressed by supernovae explosions by means of turbulent feedback. Thus, the model star formation law must depend on density and on turbulent energy of gas.

Let us adopt the star formation law in Kennicutt form [8]:

$$\psi = c_* \frac{\rho}{\tau_{\text{ff}}} , \quad (1)$$

where  $\rho$  is the gas density,  $\tau_{\text{ff}} \propto \rho^{-1/2}$  is the free-fall time,  $c_*$  is the star formation efficiency (the values are from 0.1 [16] to 1 [14]). It is commonly believed that the stars form from a dense and cool gas. It is possible to adopt this assumption in a simple manner. Just let the star formation efficiency  $c_*$  be the fraction of perturbations of density which are unstable by Jeans criterion, assuming the masses of perturbations distributed in a power law:

$$c_* \propto m_{\text{J}}^{1-\beta} , \quad (2)$$

where  $m_{\text{J}} \propto \rho^{-1/2} T^{3/2}$  is the Jeans mass [7] depending on density and “temperature”  $T$ , and  $\beta$  is the exponent of power distribution of mass of perturbations. It is necessary to explain the meaning of temperature in this expression. The temperature value averaged over all components of ISM  $\sim 10^4$  K while the temperature of the gas in star forming regions is tens and units of Kelvin. However, we can assume the local virial equilibrium between thermal and turbulent energy of gas, and the power law dependence of turbulent velocity dispersion on scale, so the value of the averaged turbulent energy will reflect the value of temperature and turbulent energy on small scales.

After all substitutions the star formation law will be

$$\text{SFR} \equiv \psi = g \rho^{\frac{1}{2}\beta+1} T^{\frac{3}{2}(1-\beta)} , \quad (3)$$

or, assuming the Salpeter-like exponent  $\beta = 2.35$ ,

$$\psi = g \frac{\rho^{2.175}}{T^{2.025}} \approx g \frac{\rho^2}{T^2}, \quad (4)$$

where  $g$  is the normalizing constant. It may be determined using the star formation law of Tutukov [19]. According to this law the star formation process is regulated by ionization and depends on gas density as

$$\psi = f \rho^2, \quad f = 2 \times 10^7 \text{ cm}^3 \text{ g}^{-1} \text{ s}^{-1}. \quad (5)$$

This law has clear physical base and it works good in the single-zone model of evolution of galaxies [20]. The average temperature of modern ISM was chosen to be  $4 \times 10^4 \text{ K}$  (though it's value does not affects significantly on the chemical abundance history of the Galaxy in single-zone evolution model, see below), so the normalizing constant becomes  $g = 3.2 \times 10^{16} \text{ cm}^3 \text{ K}^2 \text{ g}^{-1} \text{ s}^{-1}$ . The temperature  $T$  used in the last formulae supposed to relate to maximal turbulent velocity dispersion  $\sigma_0^2$  as  $\sigma_0^2 = k_B T / \mu$ , where  $k_B$  is the Boltzmann constant and  $\mu$  is the mean molecular weight.

Some star formation models with turbulent energy account had been offered earlier [1, 9], but the model proposed in this paper has the advantage. This model based on Jeans instability criterion so it can be extended for the case when the galaxy rotation, magnetic field or chemical composition is significant.

## Dissipation model

In all numerical models of galaxy evolution, the ISM in a computational cell presented as a solid 'brick' of gas without any structure. However, the ISM has complex turbulent behaviors which are needed to be allowed. In a simple approach the ISM may be considered as a set of colliding clouds with different sizes and masses. The cloud mass probability distribution function (PDF)

$$\mathbf{P}\{dM\} = \frac{dM^{1-\alpha}}{M_{\max}^{1-\alpha} - M_{\min}^{1-\alpha}}, \quad \alpha \approx 1.5 \quad (6)$$

and density dependence on scale

$$\rho_l = \rho_0 \left( \frac{l}{l_{\max}} \right)^{-r}, \quad r \approx 1.1 \quad (7)$$

are observable [18] and velocity-scale relation had examined by both observations [12] and computations [3, 9]:

$$\sigma_l^2 = \sigma_0^2 \left( \frac{l}{l_{\max}} \right)^p, \quad p \approx 1. \quad (8)$$

Here the scale  $l$  is in range  $(l_{\min}, l_{\max})$  and values  $\rho_0$  and  $\sigma_0$  are averages in an area of size  $l_{\max}$ .

Imagine that dissipation of turbulent energy occurs trough the collisions of clouds, subsequent contraction and heating by shock waves and radiation. It is obvious that the efficiency of dissipation will determine by relation of collision time to cooling time [15]. The value of energy radiated away per unit time in this process is

$$Q \equiv \left[ \frac{\text{dissipation}}{\text{rate}} \right] = \left[ \frac{\text{collision}}{\text{frequency}} \right] \sum_{l_{\min} \leq l \leq l_{\max}} \left[ \frac{\text{energy of clouds}}{\text{of size } l} \right] \times \left[ \frac{\text{fraction of}}{\text{radiated energy}} \right] \quad (9)$$

The collision rate can be estimated as  $\tau_d = \sqrt{3/(2\pi G \rho_0)}$  [4, 17]. The volume density of turbulent energy of clouds of sizes from  $l$  to  $l + dl$  is

$$\rho_0 \frac{v_l^2 + \sigma_l^2}{2} \mathbf{P}\{dl\} = \rho_0 \frac{\sigma_0^2}{2} \mathbf{P}\{dl\}, \quad (10)$$

where  $v_l^2 = \sigma_0^2 - \sigma_l^2$  is the velocity dispersion of clouds of size  $l$ .  $\mathbf{P}\{dl\}$  is the cloud size PDF which can be obtained using the simple assumption about cloud mass and density  $M_l = \rho_l l^3$ :

$$\mathbf{P}\{dl\} = \frac{dl^{1-\lambda}}{l_{\max}^{1-\lambda} - l_{\min}^{1-\lambda}}, \quad \lambda = (\alpha - 1)(3 - r) + 1 \approx 1.95 \quad (11)$$

It is reasonable to describe the fraction of radiated energy for clouds of size  $l$  by Poisson distribution  $1 - e^{-q_l}$  where  $q_l$  is the relation of the collision time to cooling time with cooling function  $\Lambda$ :

$$q_l = \tau_{\text{coll},l} \frac{\rho_{\text{sh},l}^2 \Lambda / \mu^2}{\rho_l \sigma_0^2 / 2}. \quad (12)$$

Here the cloud density  $\rho_{\text{sh},l}$  behind a shock wave and the time of collision  $\tau_{\text{coll},l}$  can be determined for the simple case of head-on collision using the one dimensional approximation, i.e. Riemann problem [11]. In this case  $\rho_{\text{sh},l} = \xi_l \rho_l$ , where  $\xi_l$  depends on  $\sigma_0$ ,  $\rho_0$  and  $l$ , and  $\tau_{\text{coll},l} = l/D_l$ , where  $D_l$  is a shock velocity which is proportional to cloud velocity:  $D_l = \eta_l v_l$ . Finally we can write  $Q = \varepsilon_d \frac{\rho_0 \sigma_0^2}{2\tau_d}$  where  $\varepsilon_d$  is the dissipation efficiency which determines by a complex expression

$$\varepsilon_d = \frac{1 - \lambda}{l_{\text{max}}^{1-\lambda} - l_{\text{min}}^{1-\lambda}} \int_{l_{\text{min}}}^{l_{\text{max}}} dl l^{-\lambda} \left( 1 - \exp \left[ - \frac{2\Lambda l_{\text{max}}}{\mu^2} \frac{\rho_0}{\sigma_0^3} \frac{\xi_l^2}{\eta_l} \frac{(l/l_{\text{max}})^{1-r}}{\sqrt{1 - (l/l_{\text{max}})^p}} \right] \right). \quad (13)$$

Strong maximum of  $\mathbf{P}\{dl\}$  in  $l = l_{\text{min}}$ , the condition  $l_{\text{min}} \ll l_{\text{max}}$  and the behaviours of  $\xi_l$  and  $D_l$  lead to simplified expression

$$\varepsilon_d = 1 - \exp \left[ - \frac{\Lambda l_{\text{max}}}{\mu^2} \frac{\rho_0}{\sigma_0^3} \right], \quad (14)$$

where the single unknown parameter is the maximal scale of turbulence  $l_{\text{max}}$ . It is set to 5 pc (this is roughly the scale of open clusters formation, the turbulence scale cannot be greater than this).

## Star formation in our Galaxy

The star formation history in galaxies can have a strongly non-monotonic nature showing a couple of bursts during a galaxy life time. Those bursts can be stimulated by an accretion of gas from intergalactic medium, collisions or close passing of galaxies. The reason to star formation to stop can be the supernovae explosions [2]. In star formation history of our Galaxy an epoch exists when the star formation process was suppressed. It is seen with distribution of  $[\text{Fe}/\text{O}]$  [6],  $[\text{Eu}/\text{Ba}] - [\text{Fe}/\text{H}]$  [13] and  $[\text{Mg}/\text{Fe}] - [\text{Fe}/\text{H}]$  [5]. This epoch may be interpreted as a pause between the end of formation of thick disk and the beginning of formation of thin disk [5, 13]. The pause corresponds to star ages between 8 – 9 and 10 – 12 Gyr.

The model of star formation and of dissipation proposed above, was taken to explain this pause in a hierarchical scenario. These models was built into the single-zone model of evolution of galaxies (Firmani & Tutukov [4]) which was initially implemented by Wiebe [20]. The detailed description of modified model and target setting has given in [10]. In modified model the star formation suppressed by collision of Galaxy and a satellite of mass  $2 \times 10^{10} M_\odot$  and radius 6.32 kpc at redshift  $z = 1.5$ . The results of modelling are presented on Fig. 1. After collision the temperature increases almost by two orders causing decrease of dissipation efficiency (see (14)) with the result that star formation process ceases due to high temperature (see (4)) for a 1.5 Gyr. The pause in star formation process is seen as a plateau on the abundance graphs  $[\text{O}/\text{H}]$  and  $[\text{Fe}/\text{H}]$  (solid line).

It is interesting to compare the abundance history with distribution of star abundance in Solar neighborhood. On Fig. (2) the  $[\text{O}/\text{H}] - [\text{Fe}/\text{O}]$  distribution is shown for near metal-poor stars [6], and the abundance history in hierarchical scenario. The arrow marks the pause of star formation which is close to the bound of populations of thick disk and thin disk. The consequence of this pause is clear: we can see the discontinuity of the stars age with continuous abundance history (see the plateau on Fig. 1). The standard model of Firmani & Tutukov [4] does not give such a plateau, giving the right position and shape of the evolution track, though.

## Conclusions

The need of taking into account the turbulent energy in star formation model is obvious. The large difference of properties of ISM on different scales is obvious also. In the present paper the model of star formation and dissipation of turbulent energy was offered and implemented to single-zone model of galaxy evolution. It is shown that the star formation history and history of chemical abundance in Solar neighborhood can be modeled in the frame of this model using the scenario of collision of the Galaxy and the small satellite.

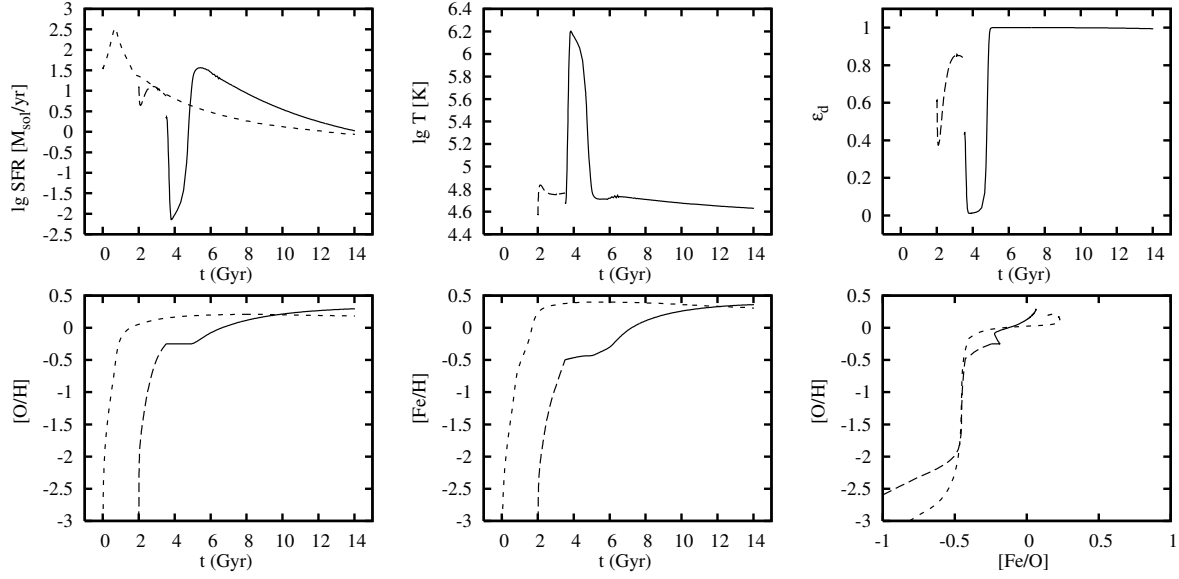


Figure 1: The results of modelling of collision of Galaxy and small satellite.  $SFR$  is the star formation rate in solar masses per year;  $T$  is the temperature;  $\epsilon_d$  is the efficiency of dissipation. Dotted line represents the standard model of Firmani & Tutukov [4], dashed line traces the evolution of a satellite before collision and solid line shows the evolution of the collision area in Galaxy, after collision.

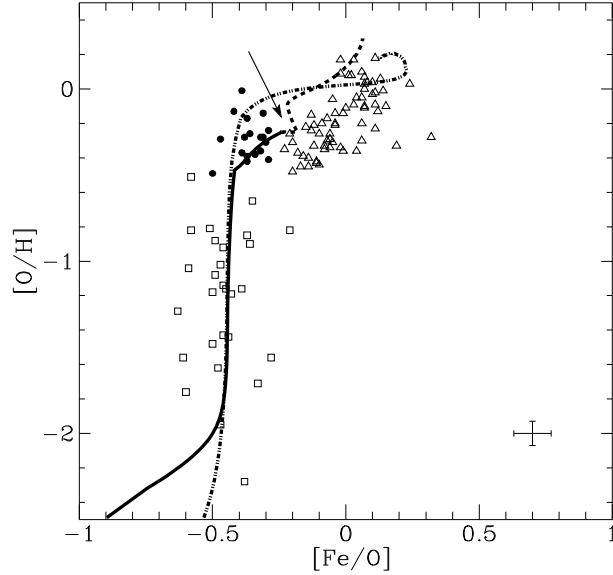


Figure 2: Evolution of chemical abundance of Galaxy in hierarchical scenario. Dot-dashed line is the standard model of Firmani & Tutukov [4], solid line is the satellite and dashed line is the collision area in Galaxy. The arrow marks the position of pause in star formation process which is seen as a plateau on the abundance graphs on Fig. 1. Symbols are halo stars (open squares), stars of the thick disk (filled circles) and thin disk (open triangles). The stars were classified using accurate stellar kinematics [6]. Error bar is at bottom right (there are same error bars for all the stars).

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## References

- [1] Berczik P. P. A&A, V. 348, pp. 371-380 (1999)
- [2] Berman B. G., Suchkov A. A. Ap&SS, V. 184, pp. 169-192 (1991)
- [3] Dobbs C. L., Bonnell I. A. MNRAS, V. 374, pp. 1115-1124 (2007)
- [4] Firmani C., Tutukov A. A&A, V. 264, pp. 37-48 (1992)
- [5] Fuhrmann K. A&A, V. 338, pp. 161-183 (1998)
- [6] Gratton R. G., Carretta E., Matteucci F., Sneden, C. A&A, V. 358, pp. 671-681 (2000)
- [7] Jeans J. H. Phil. Trans., V. 44, p. 129 (1902)
- [8] Kennicutt R. C. Jr. ApJ, V. 498, p. 541 (1998)
- [9] Krumholz M. R., McKee C. F. ApJ, V. 630, pp. 250-268 (2005)
- [10] Kurbatov E. P. Astronomicheskii Zhurnal, in press (2007), arXiv:0709.3923
- [11] Landau L. D., Lifshitz E. M. Fluid mechanics, Course of theoretical physics, Oxford: Pergamon Press (1959)
- [12] Larson R. B. MNRAS, V. 194, pp. 809-826 (1981)
- [13] Mashonkina L., Gehren T. A&A, V. 364, pp. 249-264 (2000)
- [14] Merlin E., Chiosi C. A&A, V. 457, pp. 437-453 (2006)
- [15] Miniati F., Jones T. W., Ferrara A., Ryu D. ApJ, V. 491, p. 216 (1997)
- [16] Scannapieco C., Tissera P. B., White S. D. M., Springel V. MNRAS, V. 364, pp. 552-564 (2005)
- [17] Silk J. IAU Symp. 115: Star Forming Regions, pp. 663-689 (1987)
- [18] Smith M. D. The origin of stars. London (UK): Imperial College Press, ISBN 1-86094-501-5, XIII + 248 pp. (2004)
- [19] Tutukov A. V., Krugel E., Astronomicheskii Zhurnal, V. 57, pp. 942-952 (1980)
- [20] Wiebe D. S., Tutukov A. V., Shustov, B. M., Astronomy Reports, V. 42, pp. 1-10 (1998)